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Measurement of Power Quality Effects and Energy Efficiency of Various Light Technologies

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Abstract. The paper deals with the influence on the power quality of various light technologies and measurement of their energy efficiency (lighting efficiency). A virtual power quality analyzer which enables measurement of all the power components, using the newest power models and definitions, is shortly described. Details of the measurement of harmonics generation by different light technologies are presented. A more realistic approach to the energy efficiency estimation, by the real electrical energy consumption, is proposed. This approach to the energy (lighting) efficiency estimation could be generalized to other domestic appliances, sources of harmonics.

Key words

Light technologies, virtual instrument, power quality, harmonics, energy efficiency.

1. Introduction

Light bulbs are small energy consumers, but the effect of billions of bulbs on the power consumption and on the power quality is tremendous. In the last decades, new technologies of light bulbs were developed, inspired by the goal of reducing the energy consumption and by increasing of lighting efficiency. Today a very large number of light bulbs, realized in different light technologies are in use. Since the households measure and pay only the active power, the effect of the light bulbs on the generation of harmonics, reactive power and distortion power and indirectly, the influence of the light technologies on the total power consumption is mainly not taken into detailed consideration.

Some recent papers [1-4] dedicated to this problem give a good foundation for deeper analysis of the theme. The transformation of the power in non-active power (or reactive and distortion power), which later causes a lot of negative effects and losses in the power system, should be penalized, which is possible by payment of a percentage of the non-active energy. For that purpose a complete measurement of power as well as good knowledge of the power characteristics of the appliances used in the households are necessary. The measurement of the power in the households in R. Macedonia is also done by using electricity meters measuring the active power, only.

However, through the development of the data acquisition cards and the virtual instrumentation, the conditions for design and use of cheap and integrated power meters and power quality analyzers are created.

2. Description of the measurement

A. Measurement of the power, power quality and energy (lightning) efficiency

Beginning with Budeanu, [5], many different models and definitions for powers were proposed, [6-11].

The Budeanu's model introducing apparent power S, active power P, reactive power Q and distortion power D:

$$S^2 = P^2 + Q^2 + D^2 \tag{1}$$

was criticized, but used for long time.

The distortion power D consists mainly of cross-products of voltage and current harmonics.

The active power P in [W] is the arithmetic mean value of the known function

$$P = \frac{1}{kT} \int_{\tau}^{\tau+kT} (v \cdot i) dt \tag{2}$$

The apparent power S in [VA] is the peak value of the power function and presents the product of the effective voltage and current values:

$$S = UI \tag{3}$$

Assuming an ideal sinusoidal form of voltage and current curves:

$$P = UI \cos \varphi_1 \tag{4}$$

where φ_1 is the phase shift between voltage and current.

Only for ideal sinusoidal supply the power factor PF is equal to $cos\varphi_1$.

$$PF = P / UI = \cos \varphi_1 \tag{5}$$

The distortion power D in [kVAr] could be expressed as:

$$D = U \cdot \sqrt{\sum_{v=2}^{\infty} I_v^2} \tag{6}$$

A general power theory that can provide a simultaneous common base for energy billing, evaluation of electric energy quality, detection of the major sources of waveform distortion and theoretical calculations for the design of mitigation equipment such as active filters or dynamic compensators has not yet been developed.

The IEEE working group on “non-sinusoidal situations” has suggested “practical definitions for powers”, [11]. The main difference between this definition and other definitions is that it separates the fundamental quantities P_1 and Q_1 from the rest of the apparent power components. The focus is also rather put on revenue metering than on compensation. The new definitions were developed to give guidance with respect to the quantities that should be measured for revenue purposes, engineering economic decisions and determination of major harmonic polluters.

The measurements presented in this paper are made according IEEE Std 1459/2010, IEEE Standard Definitions for the Measurement of Electric Power Quantities under Sinusoidal, Nonsinusoidal, Balanced, or Unbalanced Conditions, [12].

B. Measurement of the harmonics generation

For steady-state conditions, a nonsinusoidal periodical instantaneous voltage or current has two distinct components: the power system frequency components v_1 and i_1 and the remaining term v_H and i_H, respectively.

$$v = v_1 + v_H \tag{7}$$

and

$$i = i_1 + i_H \tag{8}$$

where

$$v_1 = \sqrt{2} \cdot V_1 \sin(\omega t - \alpha_1) \tag{9}$$

$$i_1 = \sqrt{2} \cdot I_1 \sin(\omega t - \beta_1) \tag{10}$$

$$v_H = V_0 + \sqrt{2} \cdot \sum_{h>1} V_h \sin(h\omega t - \alpha_h) \tag{11}$$

$$i_H = I_0 + \sqrt{2} \cdot \sum_{h>1} I_h \sin(h\omega t - \beta_h) \tag{12}$$

The overall deviation of a distorted wave from its fundamental harmonic can be estimated by the total harmonic distortion. The total harmonic distortion of the voltage is:

$$THD_v = \frac{V_H}{V_1} = \sqrt{\left(\frac{V}{V_1}\right)^2 - 1} \tag{13}$$

The total harmonic distortion of the current is:

$$THD_i = \frac{I_H}{I_1} = \sqrt{\left(\frac{I}{I_1}\right)^2 - 1} \tag{14}$$

The active power P [W] , the fundamental active power P_1 [W], the harmonic active power (non-fundamental active power) P_H [W], the fundamental reactive power Q_1 [VAr], the fundamental apparent power S_1 [VA], are measured according IEEE Std 1459/2010, [12].

The fundamental apparent power S_1 and its components P_1 and Q_1 are the actual quantities that define the rate of flow of the electromagnetic field energy associated with the fundamental harmonic of the voltage and the current. This is a product of high interest of the utility as well as of the end-user.

The separation of the rms current and voltage into fundamental and harmonic terms resolves the apparent power in the following manner:

$$S^2 = (VI)^2 = \left(V_1^2 + V_H^2\right) \cdot \left(I_1^2 + I_H^2\right)^2 \tag{15}$$

and

$$S_N = \sqrt{S^2 - S_1^2} \tag{16}$$

is the non-fundamental apparent power, and is resolved in the following three distinctive terms:

$$S_N^2 = D_I^2 + D_V^2 + S_H^2 \tag{17}$$

The current distortion power in [VAr] is:

$$D_I = V_1 I_H = S_1 \cdot THD_I \tag{18}$$

The voltage distortion power in [VAr] is:

$$D_V = V_H I_1 = S_1 \cdot THD_V \tag{19}$$

The harmonic apparent power in [VA] is:

$$S_H = V_H I_H = S_1 \cdot THD_I \cdot THD_V \tag{20}$$

$$S_H = \sqrt{P_H^2 + D_H^2} \tag{21}$$

The harmonic distortion power in [VAr] is:

$$D_H = \sqrt{S_H^2 - P_H^2} \tag{22}$$

The non-active power in [VAr] is:

$$N = \sqrt{S^2 - P^2} \tag{23}$$

This power lumps together both fundamental and non-fundamental non-active components. The non-active power N shall not be confused with a reactive power. Only when the waveforms are perfectly sinusoidal, $N = Q_1 = Q$.

C. *Measurement setup*

Virtual Power Meter and Analyzer

The instrument has two modules for analog inputs:

- 3-channel 300 V rms analog input module with 50 kS/s per channel simultaneous inputs for phase voltages measurement,
- 4-channel current input, 5 A rms measurement, 50 kS/s per channel simultaneous inputs and
- built–in antialias filters.

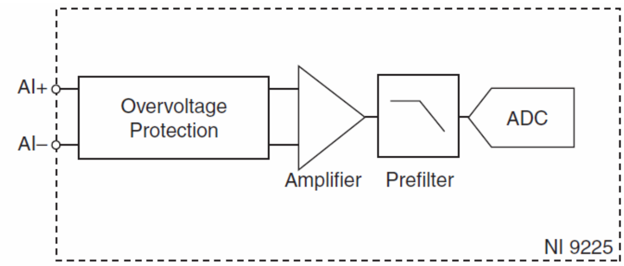

Fig.1. Input circuits for one channel of NI voltage analogue input module

The modules use a compact DAQ, 4 slot chassis with USB connection. The chassis runs the analog input modules simultaneously. The chassis has four built-in general purpose 32 bit counter/timers.

The Delta-Sigma ADCs are with 24 bits. The internal master time-base is f_M=12,8 MHz. The accuracy is ±0,23 % of the read value, ±0,05 % of the range (for temperature range from -40 °C to 70 °C).

The LabVIEW™ graphical programming language was used for creation of the virtual instrument for measurement of the power quality characteristics.

The virtual instrument beside the measurement of the phase voltages, phase and neutral currents, contains software modules running in parallel: power monitor, EN 50160 voltage monitor, FFT analyser, vector analyser, and flicker analyzer.

In Figure 2 the source code for subroutine POWER is shown.

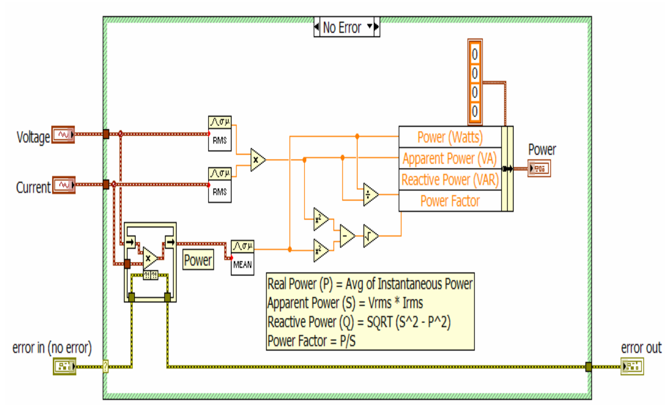

Fig.2 Block diagram-source code of the subroutine POWER

The instrument comprises few advantages: every chanel is with own ADC and the sampling of volatges and currents is simultaneous; the use of LabView™ multicore processor and dataflow programming enables paralel computing of multiple quantities. The device has the capability to do measurements using in paralel different models and definitions by diferent authors, [5-11]. It allows comparison of the results gained by different models and study of the events in the power system in different coordinates and spaces.

The instrument was calibrated by the laboratory multifuncional calibrator FLUKE 5500A, [13]. The power measurement uncertainty of the virtual instrument was estimated to ±0,3%, [14].

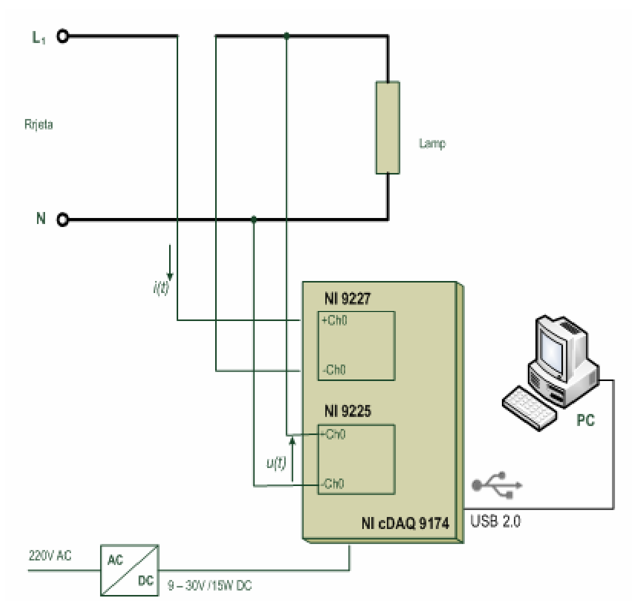

Fig. 3. Measurement arrangement

Measurement arrangement

The laboratory set-up for measuring the characteristics of different lamp technologies is given in Fig. 3.

3. Measurement Results of Power Quality and Energy Efficiency of Different Light Technologies

With the described instrument, measurements of the power characteristics and power quality influence of different light technologies are made.

The measurement were realised with the following light technologies:

1. Incandescent light bulb,
2. Fluorescent light with inductive ballast,
3. Fluorescent light with electronic ballast,
4. ECO Energy saving light,
5. LED light

The power characteristics of the ECO Energy saving light are shown on Figure 4.

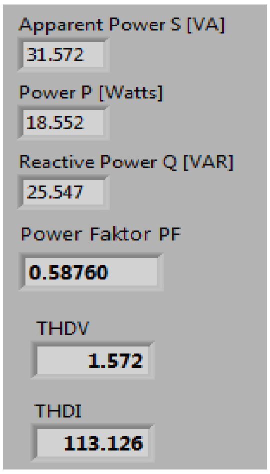

Fig. 4. Characteristics of the ECO Energy saving light

The waveforms of the current, the voltage, the total harmonic distortion of the current and the voltage as well as all the power components and characteristics are shown in Figures 5-7.

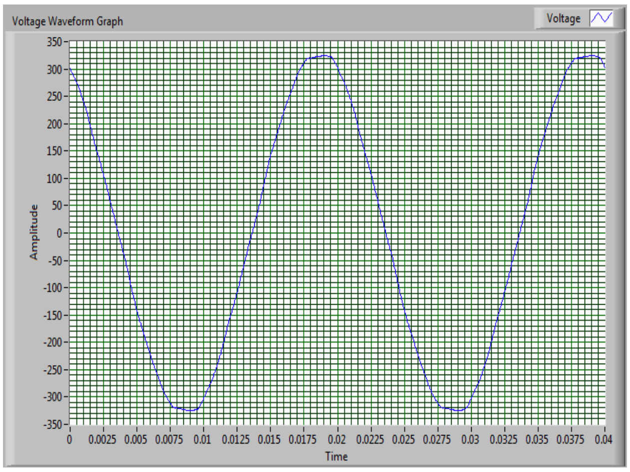

Fig. 5. Voltage waveform graphs of ECO Energy saving light, THD_V=1,57 %

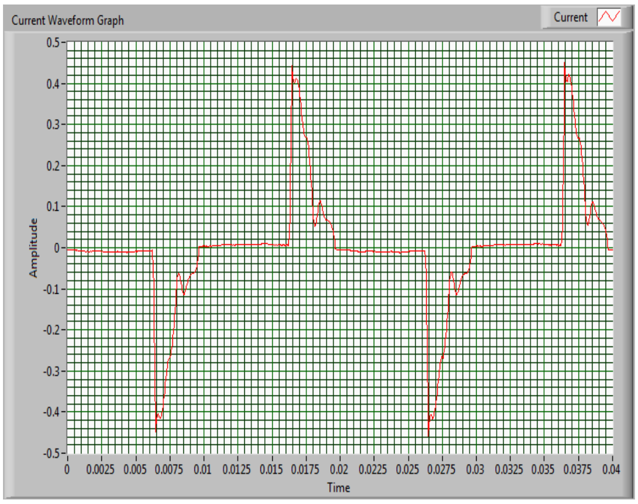

Fig. 6. Current waveform graphs of ECO Energy saving light, THD_I=113,12%

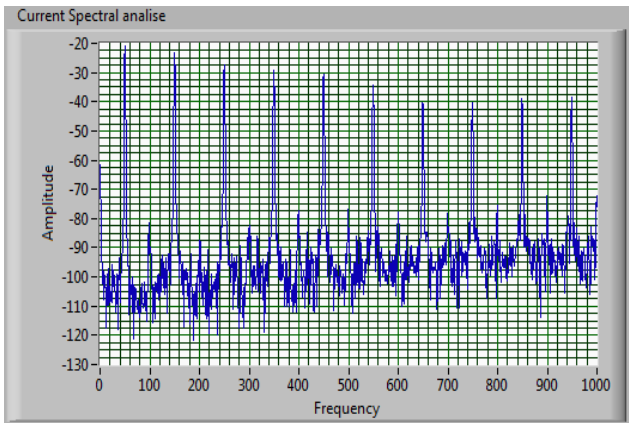

Fig. 7. Current spectral analysis for ECO Energy saving light

The measurements according IEEE Standard Definitions gives the results shown on Figure 6.

Considering that the generation of harmonics is very high (THD_I=113,12 %), the part of the non-active power which creates losses in the system should be taken into account during the estimation of the efficiency of the light technology. By taking into account the known effects (conductors heating, transformers heating, transformer losses etc.) it can be estimated that 1/3 of the non-active power should be added to consumed active power when the efficiency is evaluated. In that way the declared efficacy by the producer (57,6 lm/W) should be corrected.

The same measurements are made with all the listed light sources and are presented in Table I.

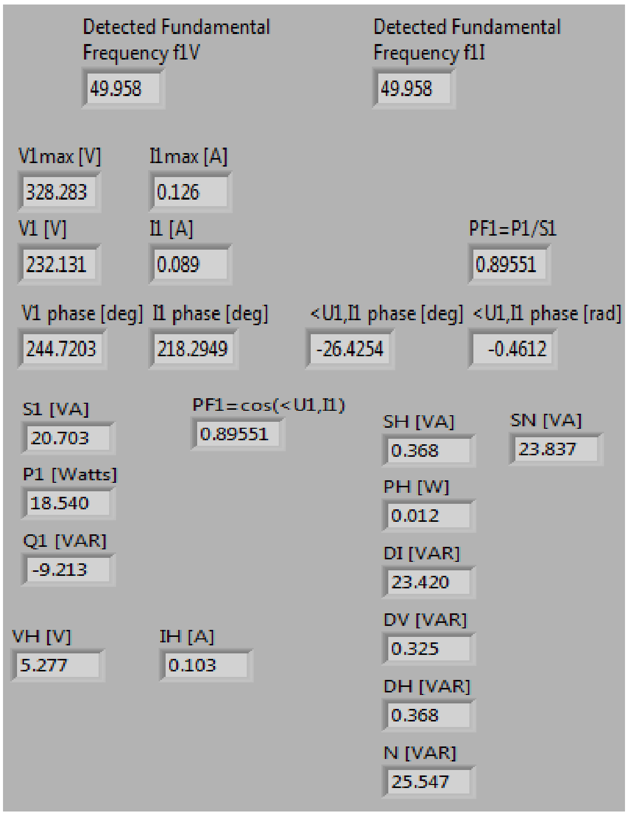

Fig. 8. Power measurements according IEEE Std. 1459 for ECO Energy saving light

Table I. – Power quality and efficiency of the light sources

Light Technology	Active Power [W]	Non-active Power [VAr]	PF	THD_V [%]	THD_I [%]	Declared Lighting Efficiency [lm/W]	Estimated Lighting Efficiency [lm/W]
Incandescent light bulb	98,9	0,87	0,999	1,59	1,54	13,4	13,36
ECO Energy saving light	18,55	25,55	0,587	1,57	113,13	57,6	43,31
Fluorescent light with inductive ballast	69,76	125,62	0,48	1,52	11,42	70,0	43,74
Fluorescent light with electronic ballast	15,15	9,61	0,84	1,47	19,35	77,5	64,02
LED light	27,37	11,48	0,92	1,36	15,03	80,3	70,45

It is obvious that the power factor and the harmonic distortion vary significantly, depending on the light bulb technology. The power factor of the fluorescent light with inductive ballast and the ECO Energy saving light is rather low.

The energy conversion efficiency should be considered together with the complete power characteristics of the light technologies.

4. Conclusion

The paper presented the measurements of power quality and energy efficiency of various light technologies. The measurements were realised by a virtual instrument for power measurements and power quality monitoring, based on simultaneous measurements of electrical voltages and currents. The virtual instrument-power meter and analyser enabled accurate and versatile measurement of power characteristics under non-sinusoidal conditions. Different advanced mathematical models are also applied in the presented methodology.

The measurements of the harmonics generation by the different light technologies and the comparison of their PQ characteristics have shown that their influence on the power quality may be significant. A more realistic approach to the energy efficiency estimation, by the real electrical energy consumption, was proposed. The non-active power generated by the different light sources may annulate the advantages of the energy saving. The conclusions about the energy efficiency of particular light technology should be reconsidered with respect of the power quality effects. There is a need for future study of the PQ influence of different household appliances and monitoring of the influence of the clusters of appliances and households on the distribution system.

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